Atmósfera (1995), 8, pp. 45-51

SHORT CONTRIBUTION

Momentum diffusivity profiles in and above a forest canopy

N. M. ZOUMAKIS

Laboratory of Atmospheric Physics, Technological Education Institute of Macedonia

P. O. Box 14561, T. E. I. Sindos 54101, Thessaloniki, Greece

(Manuscript received March 22, 1994; accepted May 30, 1994)

RESUMEN

Unas formulaciones semiempíricas y teóricas que han sido propuestas para describir los perfiles de rapidez media eólica de la capa de transición (Zoumakis, 1992c; 1993c; 1993d; 1994) se utilizan para deducir relaciones entre la longitud de rugosidad z_o, el desplazamiento del plano cero y la profundidad $z*$ de la capa de transición, y para estimar los coeficientes de difusión K de los mecanismos de transferencia torbellinaria dentro y arriba del dosel de la vegetación alta y forestal.

Las estimaciones teóricas de d, z_o, $z*$ y K se comparan bien con datos provenientes de varias fuentes y el análisis teórico de Thom (1971), Landsberg and Jarvis (1973), Bache (1986) and Zoumakis (1994).

ABSTRACT

Semi-empirical and theoretical formulations which have been proposed to describe the transition-layer mean wind-speed profiles (Zoumakis, 1992c; 1993c; 1993d; 1994) are used to derive relationships between the roughness length z_o, zero-plane displacement d, and transition-layer depth $z*$, and to estimate the diffusivity coefficients K of turbulence transfer mechanisms within and above tall vegetation and forest canopies. The theoretical estimates of d, z_o, $z*$ and K compare well with data from various sources and the theoretical analysis from Thom (1971), Landsberg and Jarvis (1973), Bache (1986) and Zoumakis (1994).

1. Introduction

The atmospheric surface layer characteristic scales are determined on the basis of the Monin-Obukhov similarity theory, as functions of the bulk Richardson number (Zoumakis and Kelessis, 1991a, 1991b, 1993; Zoumakis, 1992a, 1992b, 1993a, 1993b). However, deviations from the modified logarithmic wind profile (Zoumakis and Kelessis, 1991c) have been observed in the wind tunnel (Raupach *et al.*, 1980) and for atmospheric observations over forest (Garratt, 1980). Moreover, the theoretical analysis confirms a lower height limit to the validity of the Monin-Obukhov functions in stable and unstable surface layer. On the other hand, the limitations of applying gradient diffusion theory to model turbulent transport within the canopy roughness layer are widely recognized (Raupach and Thom, 1981).

2. Methodology and discussion

Assuming that the air is incompressible and that density is constant with height, the mass-conservation principle can be written in neutral stability (Molion and Moore, 1983; DeBruin and Moore, 1984; Lo, 1990):

$$\int_{d+z_o}^{z_f} u_L(z)dz = \int_o^{z_f} u_m(z)dz \tag{1}$$

where $u_m(z)$ represents the actual wind profile, d is the zero-plane displacement, z_o is the roughness lenght, z_f represents a level within the logarithmic regime, and $u_L(z)$ is the logarithmic wind profile in neutral stability conditions:

$$u_L(z) = \frac{u_*}{k} \ln\left(\frac{z-d}{z_o}\right) \tag{2}$$

where $u*$ is the friction velocity and k is von Karman's constant. DeBruin and Moore (1984) assume a mean neutral wind speed profile (as illustrated in their Fig. 1) measured within and above Thetford Forest, designed to give equal mass flows between ground and z_f (as indicated by equal areas A and B), for which direction and curvature are free of discontinuities. The solid curve in Figure 1a represents the mean wind speed profile $u_m(z)$ within and above Thetford Forest computed with the empirical formula:

$$\mu - [u_m(z)/u_L(z_f)] = C\{1 + [(C - N_o)/N_o] \exp[-(z_f - z)\gamma(z)]\}^{-1}, \quad 0 \le z \le z* \tag{3}$$

where $z*$ is the transition–layer depth, and μ, C, N_o and $\gamma(z)$ denote positive constants that depend upon the particular aerodynamic characteristics of the canopy (Zoumakis, 1992c, 1993d). The transition–layer profile of the eddy diffusion coefficient K for momentum transfer may be obtained by using the diffusivity equation (flux–gradient approach):

$$K\frac{\partial u_T}{\partial z} = u_*^2, \quad h \le z \le z* \tag{4}$$

where h is the mean height of roughness elements, and $u_T(z)$ represents the wind profile within the transition zone. By introducing Equation (3) into Equation (4), we obtain the transition–layer profiles of the momentum diffusivity ratio $K(z)/K(h)$ based on observations of DeBruin and Moore (1984) and Oliver (1971), taken from above and within a forest canopy (illustrated in Fig. 1b and 1c, respectively).

Extending the measure velocity profile $u_m(z)$ to higher levels ($z_f \le z \le z*$), from Equation (1) yields (Zoumakis, 1993c):

$$\int_{d+z_o}^{z_*} u_L(z)dz = \int_o^{z_f} u_m(z)dz + \int_{z_f}^{z_*} u_T(z)dz \tag{5}$$

where $u_T(z)$ is the empirical modification of the wind-speed profile in the transition layer suggested by Garratt (1980). However, Cionco (1985) proposed that a realistic model should consist of a microscale within the forest canopy coupled with the mesoscale flow field above.

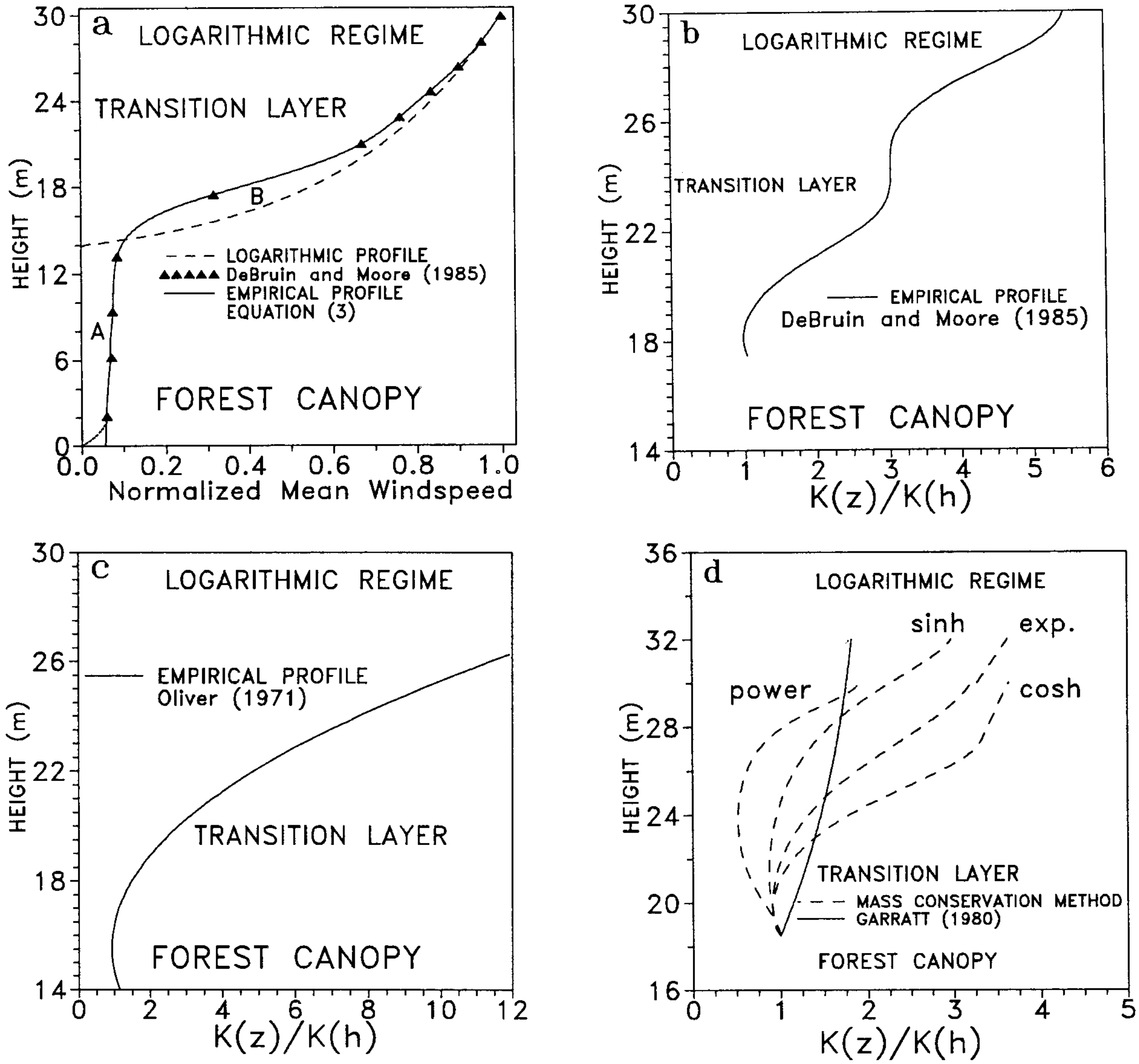

Fig. 1. (a) Normalized mean neutral wind-speed profile in and above a forest canopy (solid line) computed with the empirical formula (3) and designed from the principle of mass conservation [Eq. (1)] to give equal mass flows between ground and $z*$, as indicated by equal areas A and B. (b) and (c). The transition-layer profiles of the momentum diffusivity ratio based on observations of DeBruin and Moore (1984) and Oliver (1971), respectively, taken within and above a forest canopy. (d) $K(z)/K(h)$-profiles within the transition zone (dashed lines) predicted from the mass-conservation method, for the exponential, cosh, power-law, and sinh canopy wind profiles. Garratt's (1980) approach is illustrated in Figure 1d as solid line.

Substituting the low wind-speed measurements $u_m(z)$ within the forest canopy by a theoretical canopy wind profile $u_C(z)$, from Equation (5) yields (Zoumakis, 1994):

$$\int_{d+z_o}^{z_*} u_L(z)dz = \int_o^h u_C(z)dz + \int_h^{z_*} u_T(z)dz \tag{6}$$

where the transition-layer profile $u_T(z)$ of mean wind-speed can be expressed as a fifth-order polynomial form joining positions $[h,\ u_c(h)]$ and $[z_* u_L(z_*)]$, for which direction and curvature are free of discontinuities (i.e., we assume a polynomial form having second–order osculation together with the principle of mass conservation). For a more detailed description of the method, see Zoumakis (1994). By introducing the exponential (exp.), hyperbolic consine (cosh), power–law, and hyperbolic sine (sinh) canopy wind–speed profiles, into Equation (4), we obtain the transition–layer profiles of the momentum diffusivity ration $K(z)/K(h)$ (illustrated in Fig. 1d as dashed lines), for each of the four different canopy types described in Figures 1 and 6a of Zoumakis (1994). It follows from Figure 1b, 1c and 1d that the momentum diffusivity decreases within the lower part of the transition layer, but increases in the upper layers. Moreover, the canopy mean wind structure has a major influence on the shape of the transition–layer diffusivity profile for momentum transfer. Also it is seen, that despite the separate models of canopy mean wind structure, the predicted diffusivity profiles are broadly consistent. However, Figures 1b, 1c and 1d present a veiw which is radically different from the (traditionally) expected behaviour of the momentum diffusivity ratio $K(z)/K(h)$ within the transition zone. For example, Raupach *et al.* (1980) assume that the diffusivity within the transition layer is constant with the height. On the other hand, Garratt (1980) suggested a monotonically increasing behaviour of the momentum diffusivity ration $K(z)/K(h)$ within the transition zone (shown in Fig. 1d as solid line). In contrast, the momentum diffusivity ratio presented in Figures 1b, 1c and 1d is seen to be in excellent agreement with the behaviour of $K(z)$: (i) in the logarithmic regime, where $K(z) = ku_*(z - d)$, and (ii) in the upper layers of the canopy, here $K(z)/K(h) > 1$, as reported by Tohm (1971), Landsberg and Jarvis (1973), Bache (1986) and Zoumakis (1994).

With the assumption of an exponential–variation of wind speed with height in the upper layers of a forest canopy (with a vertical structure of Gaussian form), the momentum diffusivity ratio within the canopy can be obtained from the relation (Bache 1986):

$$\frac{K(z)}{K(h)} = \exp\left\{\alpha\left(1 - \frac{z}{h}\right)\right\}\frac{\tau(z)}{\tau(h)}, \qquad z \leq h, \tag{7}$$

with

$$\frac{\tau(z)}{\tau(h)} = \frac{\operatorname{erf}\left(\frac{z-\beta_o}{s}\right) + \operatorname{erf}\left(\frac{\beta_o - b_o}{s}\right)}{\operatorname{erf}\left(\frac{h-\beta_o}{s}\right) + \operatorname{erf}\left(\frac{\beta_o - b_o}{s}\right)},$$

where $\beta_o = h_m + (2 - n)(\alpha\sigma^2/h)$, $b_o = 2h_m - h$, $s^2 = 2\sigma^2$, $\tau(z)$ is the shear stress profile, α is the profile extinction coefficient, n is an empirical coefficient (independent of wind speed) and h_m defines the position of maximum foliage density with σ as a distribution function. For a more detailed description of the method, see Bache (1986). The profile of the momentum diffusivity ratio $K(z)/K(h)$ within and above a Gaussian forest canopy (with the tentative assumption of $h_m = 0.69h$, $\sigma = 2$m and $n = 0.22$) is illustrated in Figure 2. It is obvious then that the theoretical cusp at $z = h$ in the K–profile (described in Bache, 1986) may be removed by adopting the osculation polynomial $u_T(z)$ described in Zoumakis (1994), as a substitute for the transition–layer mean wind–speed profile. Moreover, the tendency to produce a transition–layer momentum diffusivity profile (dashed line) consistent with the expected structure of K within the forest canopy (solid line) and the expected K–profile within the logarithmic regime (dot line) is also clearly shown in Figure 2.

When modelling boundary–layer flow over a forest canopy, so long as the idealized flow field over the hypothetical lower boundary typically characterized by parameters such as z_o and d can

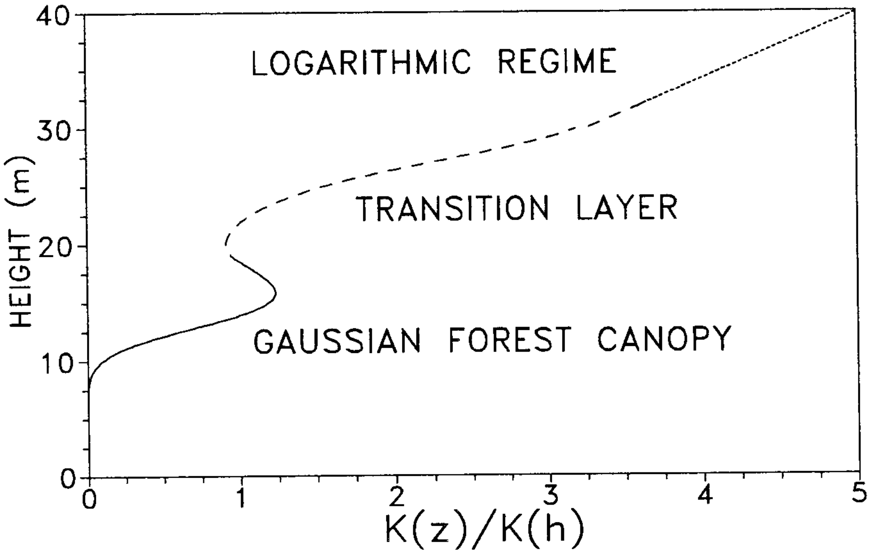

Fig. 2. The predicted $\{K(z)/K(h)\}$-profile within (solid line) and above (dashed line) a Gaussian forest canopy. The profile of the momentum diffusivity ratio within the logarithmic regime is illustrated in Figure 2 as dot line.

properly represent the effects of the underlying canopy on the atmospheric boundary layer, the approach should provide a reasonable approximation for describing the behaviour of the mean flow field (Lo, 1990). Zoumakis (1993c) and (1994) however, pointed out that the choice of a value for $z*$ can significantly affect the analysis of the parameters d and z_o. Thus, it is important to establish a scheme for determining $z*$, in terms of the particular physical characteristics of the canopy. Based on Equation (6), Figure 3a shows the relation between $z*$ and d (for various values of z_o) for the exponential-like (dashed lines) and hyperbolic cosine-like (solid lines) canopy wind-speed profiles discussed in Figure 1d. Figure 3b presents the expected increasing (almost

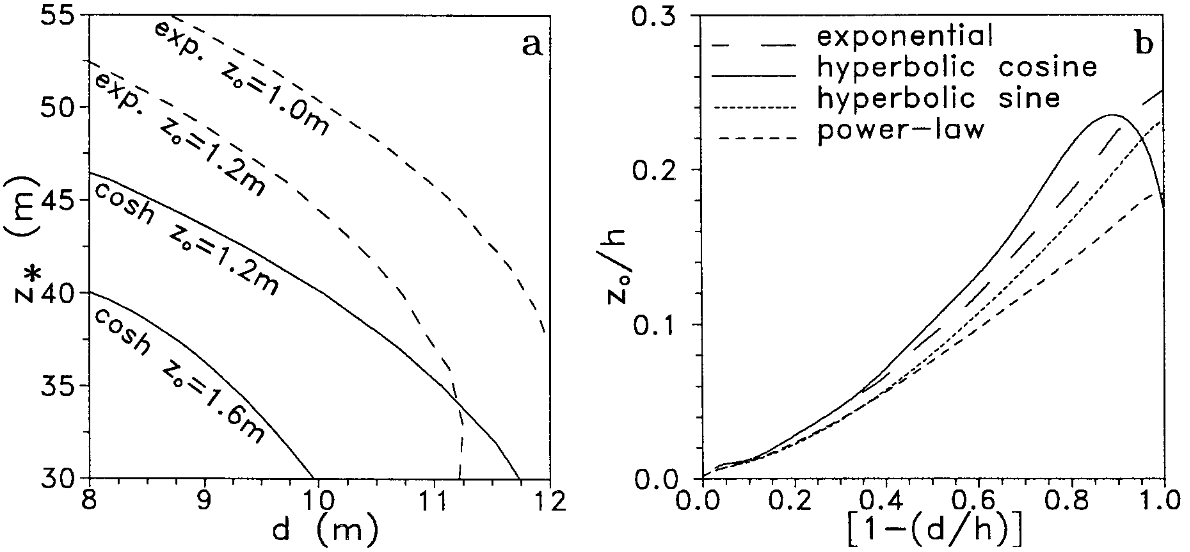

Fig. 3. (a) $z*$ as a function of d, for the cosh (solid line) and exponential (dashed line) canopy wind profiles, for different values of z_o. (b) Normalized roughness height, z_o/h, as a function of $[1 - (d/h)]$, for each of the four different types of canopy wind-speed profiles (exp., cosh, power and sinh) discussed in Figure 1d.

linear) behaviour of the normalized roughness length z_0/h, as a function of $[1-(d/h)]$ (Thom, 1971), for each of the four different types of canopy wind-speed profiles (exp., cosh, power and sinh) discussed in Figure 1d. The predicted forms of the relationship between z_0/h and d/h are strongly dependent on the vertical structure of the canopy, e.g., the shape of the mean wind speed profile (at least) in the upper canopy (Zoumakis, 1994). Moreover, a line forced though the origin to satisfy the equation $z_0/h=\lambda(1-d/h)$ has a slope of about $\lambda=0.22-0.29$. This is close to the experimental value of the specific density of the main roughness elements quoted earlier for real and artificial crops and for a forest (e.g., Thom, 1971; Seginer, 1974; Shaw and Pereira, 1982; DeBruin and Moore, 1984; Massman, 1987). However, the predicted z_0/h corresponding to the hyperbolic cosine (cosh) canopy wind-speed profile (illustrated in Figure 3b as solid line), initially increased with decreasing d/h as $d\rightarrow 0$ reached a peack, and then declined, which qualitatively agrees with the deductions of Shaw and Pereira (1982) and Massman (1987).

In conclusion, because of the computational simplicity of the proposed methodology, it may profitably be used for simulating airflow for use within large-scale plant-atmosphere exchange models.

Acknowledgement

This work has been partly supported by the Research Committee of the Technological Education Institute (T. E. I.) of Thessaloniki.

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